Energy consumption and intensity of toll highway transport in Spain

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A B S T R A C T

We estimate the energy consumption of toll highway transport on a number of Spanish roads. Regression parameters are balanced according to coefficients from an empirical analysis based on survey data by vehicle type. The mean energy consumption and subsequent CO_2 emissions on the toll highway sections are estimated as 1895 MJ/h/lane-km and 0.15 tCO_2 eq./h/lane-km, values that increase to 2644 and 0.22 when energy and carbon emissions of transport infrastructure are considered based on the life cycle energy consumption for toll highway construction and use. If the energy intensity of infrastructure construction is allocated to the users according to traffic, it is much higher for motorcycles than for cars, and is significantly lower for articulated trucks than for vans.

1. Introduction

Energy savings through reduction of road transport demand on highways has traditionally focused on external cost amelioration related mostly to CO_2 and pollutant emissions; decreasing the energy intensity (*EI*) has generally been less explored. However, the importance of *EI* is currently increasing, and there are some studies focused on the monitoring of energy and environmental transport impacts per service unit offered. These studies are based on the development of transport sustainability, life cycle analysis (*LCA*) and intensity indicators. For instance, the material input per service unit (*MIP*) measures the potential for reducing energy and environmental impacts of transport per unit of product or service offered, thus serving as a transport intensity indicator.

Modal absolute energy consumption depends to a large extent on the amounts transported; be it passengers or tons. Activity data and energy consumption are used to analyze the intensity because it is determined by the energy required to move a vehicle and way its capacity is used. The energy required is determined by its fuel consumption, transport conditions, and vehicle characteristics. The use of its capacity depends upon occupancy and its load, its use, and the distribution of vehicles types in a fleet as a whole.

2. Data and methodology

Traffic on the 2928 km of Spain's high-capacity network toll highways in 2007 was 25,074 million vehicle-km, with an average daily flow (AADT) of 23,462. The Spanish Road Traffic Survey (SRTS) provides data on vehicle fleet distribution (MFO, 2009a): 76.2% of the traffic is cars, 12.8%, trucks, 1.4% buses, 8.4% vans, and 1.2% motorcycles. The traffic data originates from permanent monitoring stations on sections of some Spanish toll highways and we focuses on toll roads because

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Table 1
Traffic flow parameters for Spanish toll highways (2007). *Source:* Ministry of Public Works.

Traffic parameter	Symbol	Mean	SD	Min	Max	Median	CV	Units
Annual average daily traffic	AADT	35,002	31,936	2,516	150,513	23,074	91	veh/day
Annual average hourly traffic per lane	AAHT	560	402	46	1,816	454	72	veh/h/lane
Traffic density	D	5.76	5.81	0.41	49.7	4.08	101	veh/km/lane
Average travel speed	v	106.2	10.2	36.5	111.9	111.0	10	km/h
% AADT in the peak-hour	k	0.07	0.00	0.06	0.08	0.07	6	%
% Peak-hour traffic in the peak direction	d	0.56	0.04	0.51	0.67	0.55	8	%
Number of lanes per direction	η	2.3	0.5	2.0	4.0	2.0	21	lanes
Hourly volume gasoline cars	AAHT car g	119	91	11	419	89	77	veh/h/lane
Hourly volume diesel cars	AAHT car d	287	220	26	1,015	215	77	veh/h/lane
Hourly volume vans	AAHT van	57	47	3	235	45	82	veh/h/lane
Hourly volume motorcycles	AAHT motorcycle	6	12	0	87	2	212	veh/h/lane
Hourly volume articulated heavy vehicles	AAHT art. truck	54	40	1	160	48	74	veh/h/lane
Hourly volume rigid vehicles	AAHT rig. truck	36	27	1	139	33	75	veh/h/lane
Hourly volume buses	AAHT bus	2	2	0	9	1	81	veh/h/lane
Proportion of heavy duty traffic	p	14.3	8.2	1.5	43.0	14.0	57.1	%

these are less used and thus offer a larger margin for improving their energy efficiency and it is easier to define suitable policies to reduce energy consumption and emissions. We consider the case of 202 sections in 2007, 1869 km in length, involving 19,837 million-vehicle-km and carrying 35,002 vehicles per day. Micro-level traffic parameters, such as AADT, percentage of HDVs (p-HDV), mean speed (v) and annual average hourly traffic (AAHT) per lane are examined. The sections average 2.3 lanes in each direction with passenger cars dominating the traffic flow at 29,384 vehicles per day average over working days and weekends. HDVs account for about 14.3% of traffic, although significantly less on weekends. Table 1 contains details.

The method used to estimate the energy consumption and CO_2 emissions from the highways is similar to that used by the Spanish Ministry of Environment (MMA, 2009) for the national emission inventory (NEI), and based on the EU Corinair report (EMEP/CORINAIR, 2009). Vehicle category and fuel consumption data for 2007 (MFO, 2009a) is used, combined with the permanent road freight sample survey (PRFSS), the road transport passenger survey (MFO, 2009b) and fuel-efficiency data from the Copert model (Ntziachristos and Samaras, 2000). The Corinair fuel consumption factors (f), is adapted to Spanish traffic conditions on toll highways, driving standards and fuel characteristics to estimate energy consumption and CO_2 emissions.

The energy consumption and CO_2 emissions of a toll highway section k are estimated using:

$$E_k = \sum_i \sum_j f_{i,j} \cdot NCV_j \cdot AAHT_{i,j} \tag{1}$$

$$C_{k,i} = E_{k,i,j} \cdot CEF_j \tag{2}$$

where E_k is the energy consumption of section k, expressed in mega-joules (MJ = 10^6 J) per hour and lane kilometre (MJ/h/lane-km); $f_{i,j}$ is the fuel consumption factor of vehicle type i using energy source j, in grams of oil equivalent per vehicle-kilometre (goe/vehicle-km); NCV_j is the net calorific value of fuel j, in MJ per goe (MJ/goe); $AAHT_{i,j}$ is the traffic of vehicle type i using energy source j, in vehicles per hour and per lane (vehicle/h/lane); C_k are the CO_2 emissions of section k, in tons of CO_2 equivalent (tCO_2 eq.) per hour and lane kilometre (tCO_2 eq./h/lane-km), and CEF_j is the carbon emission factor for fuel j, in tons of CO_2 equivalent per tera-joule (TJ = 10^{12} J, tCO_2 eq./TJ). Fuel consumption available in grams of gasoline and diesel per hour lane-km (goe/h/lane-km), are converted into energy units (mega-joules, MJ) using the fuel's *NCV*. Analogously, CO_2 emissions are estimated in tons of CO_2 from energy consumption through the *CEF*.[1]

Uncertainties in the estimation of energy consumption and CO_2 emissions can be addressed by an appropriate allocation of activity and fuel data across types of road vehicles (Kühlwein and Friedrich, 2005). Therefore, appropriate country-specific Corinair fuel consumption factors must be used. Based on the distribution of the Spanish fleet (by vehicle type and age), technology of vehicles (EURO emission standards) and engine capacity, the mean consumption factors from the Copert model were weighted. These factors characterise the mean energy consumption of vehicles and are related to vehicle operation speed (v). The weighting parameters used in the estimation of the consumption factors are summarised in Table 2 for all age groups and engine capacities (LDVs) and for all age groups, load capacities and load factors (HDVs).

Consumption factors depend on vehicle speed (v); the slope coefficient, which measures the percentage effect of the slope of the highway section (s), and the roughness coefficient, which measures the effect of the international roughness index (r) in mm/m. Fuel consumption increases as s and r increase. Park and Rakha (2006) looking at slope effects on the fuel consumption of Californian vans in a free flow scenario and at a constant speed of 64 km/h found an increase in fuel consumption of 140% when the slope increased increases from 0% to 6% (from 68.1 to 163.5 goe/km). Boriboonsomsin and Barth (2009) found a similar relationship. At a constant speed of 96 km/h, an increase in section slope of 6% results in a 138.3%

[1] The *NCV* and *CEF* values used are from Schipper (2009): 0.036 MJ/goe (gasoline), 0.039 MJ/goe (diesel), 86 tCO_2 eq./TJ (gasoline) and 81 tCO_2 eq./TJ (diesel).

Table 2
Summary table including weighting parameters used in fuel consumption factor estimation.

Vehicle type	Technology (EURO)	Engine capacity (l), GVW (t)	Loading factor (no units)
LDVs			
Gasoline cars	After EURO I (66.0%)	<1.4 l (46.8%)	–
		1.4–2 l (41.8%)	
		>2 l (11.4%)	
Diesel cars	EURO IV (31.8%)	<2 l (88.7%)	–
	EURO III (32.3%)		
	EURO II (26.2%)		
Diesel vans	After EURO I (80.6%)	–	–
Motorcycles	Prev. EURO I (38.5%)	<0.25 l (<50%)	–
		Four times (90.6%)	
HDVs			
Articulated trucks	After EURO II (62.7%)	<28 t (56.9%)	Full load (38.5%)
		28–40 t (31.8%)	Half load (38.5%)
		>40 t (11.3%)	Empty (22.9%)
Rigid trucks	After EURO II (62.7%)	<12 t (23.5%)	Full load (37.5%)
		28–40 t (28.8%)	Half load (37.5%)
		28–40 t (25.2%)	Empty (25.0%)
		28–40 t (19.0%)	
		>40 t (3.5%)	
Buses	After EURO II (59.4%)	<18 t (56.9%)	Full load (34.5%)
		>18 t (11.3%)	Half load (34.5%)
			Empty (31.0%)

increase in gasoline car consumption from 42.1 to 100.4 goe/km. The Copert model also measures the effect of slope on energy consumption by HDVs.

In terms of the influence of highway surface on energy consumption, Cenek (1994) finds that a decrease in r from 5.7 to 2.7 results in a 4% reduction in fuel consumption by LDVs, while Burguess and Choi (2003) find a 10% potential improvement in r and a subsequent 3% reduction in fuel consumption by LDVs in the UK. Road pavement has only a minor effect because all highway sections have bituminous surfaces. Depending on speed, we assume that a 5% increase in the slope of the highway results in a 50–160% increase in consumption by LDVs and a 60–220% by HDVs. The effect of roughness of the pavement on consumption is much lower; a 5–15% increase for LDVs and a 6–20% for HDVs.

Calculation of the *EI* of Spanish toll highways during the exploitation phase is based on data on the construction of the transport infrastructures and data on the use of vehicles. The *EI* of toll highway transport section k, vehicle i and fuel j, expressed in MJ per vehicle-km (MJ/vehicle-km), is estimated using:

$$EI_{k,i,j} = \left[X_k \cdot \left(\frac{1}{AADT_k \cdot p_{i,j} \cdot 365 \cdot cv_k}\right) + Y_{i,j}\left(\frac{1}{cv_{i,j}}\right)\right] \tag{3}$$

where X_k is the intensity of infrastructure k (MJ/km), $AADT_k$ is the annual average daily traffic on toll highway section k (vehicles/day), $p_{i,j}$ is the percentage of average daily traffic related to vehicle type i using fuel technology j, cv_k is the life cycle of infrastructure k (30 years), $Y_{i,j}$ is the intensity of vehicle i and fuel j (MJ/vehicle) and $cv_{i,j}$ is the life cycle of vehicle i using fuel j (270×10^3 gasoline and diesel car kilometres, 400×10^3 diesel van kilometres and 1000×10^3 truck kilometres). The mean value of infrastructure intensity is assumed to be 28.1×10^6 MJ per kilometre (González Díaz and García Navarro, 2009). The equation has two parts: the infrastructure's life cycle energy consumption divided by the traffic during the road's service life of 30 years and the vehicles' life cycle energy consumption divided by the number of kilometres driven. The second part relates to vehicle consumption factors ($f_{i,j}$ in MJ per vehicle-km) where Y is defined by multiplying $f_{i,j}$, NCV_j and $cv_{i,j}$, and relates to Eqs. (1) and (2). The parameter estimates are calculated for each section.

Dividing Eq. (3) by the number of passengers and freight tonnage transported, Eq. (4) gives MJ per passenger-km or ton-km (MJ/p-km, MJ/t-km):

$$EI^{*}_{k,i,j} = \frac{EI_{k,i,j}}{fo_{i,j}} \tag{4}$$

where $fo_{i,j}$ is the occupancy rate or load factor of i and j, assuming an average capacity utilisation for motorcycles, cars and buses of 1.2, 1.9 and 18 passengers. The average tonnages transported of vans, rigid trucks and articulated trucks are 0.5, 4.5 and 7.2 tons (MFO, 2009b).

Finally, the aggregate *EI* of toll highway section k is estimated in mega-joules per transport unit (tu) kilometre (MJ/tu-km, tu: passenger-km: ton-km) using:

$$EI^{*}_{k} = \sum_i \sum_j p_{i,j} \cdot EI^{*}_{k,i,j} \tag{5}$$

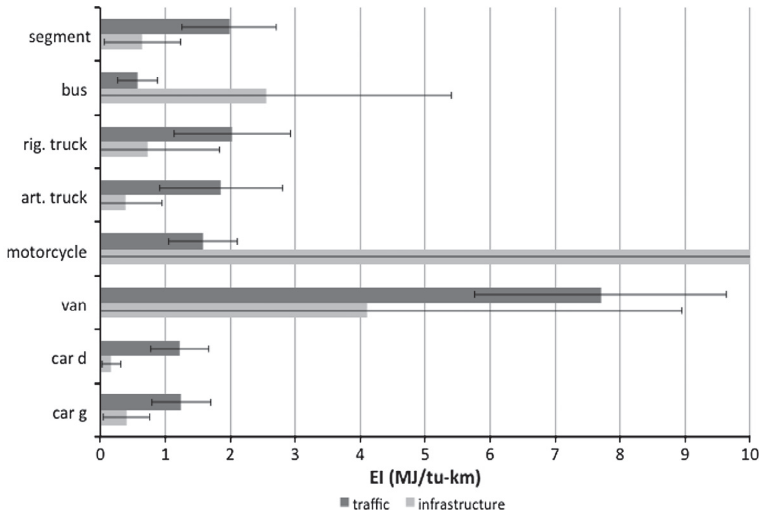

Fig. 1. *EI* estimates, infrastructure and traffic, for passenger and freight transport vehicles with infrastructure allocated according to traffic. *Note:* Error bars represent *EI* uncertainty expressed as standard deviation of section estimates; *EI* (infrastructure) of van and motorcycle from 4.1 to 27.5 MJ per transport unit kilometre.

where $p_{i,j}$ is the percentage of vehicle type i using fuel j when the infrastructure is allocated according to traffic volume by vehicle type (tu is 1 passenger-km and 1 ton-km).

3. Results

Estimates of mean energy consumption and CO_2 emissions broken down by vehicle type are calculated using data from different sources. The mean energy consumption and subsequent CO_2 emissions on the toll highway sections are estimated to be 1895 (±1215) MJ/h/lane-km and 0.15 (±0.10) tCO_2 eq./h/lane-km; the numbers in parentheses represent the uncertainties estimated by the standard deviation of the mean. These values increase to 2644 and 0.22 when energy and carbon emissions of the transport infrastructure are considered; about 28% of energy is attributed to infrastructure construction and maintenance. The mean energy consumption broken down by vehicles categories is 345 MJ/h/lane-km for gasoline cars, 672 for diesel cars, 292 for vans, 116 for motorcycles, 707 for articulated trucks, 387 for rigid trucks and 124 for buses. Freight vehicles, with an average of 1386 MJ/h/lane-km, have the greatest energy consumption and CO_2 emissions.

EI estimates by vehicle type are calculated using Eqs. (4) and (5) (Fig. 1) and broken down by traffic and transport infrastructure use. Large differences in average *EI* in terms of mega-joules consumed per tu-km can be seen between vehicles. The calculations suggest Spain's tolled highway sections require 2.6 MJ/tu-km; 0.6 infrastructure and 2.0 traffic use of energy, varying between 1.4 for diesel cars, and 29.1 for motorcycles. Similarly, in aggregate, gasoline car and diesel van transport requires between 1.6 and 11.8 MJ/tu-km; values are similar to those found in Saari et al. (2007) and Pérez-Martínez and Sorba (2010).

Considering traffic use, as expected, mass passenger modes consume less energy per transport unit than private transport, while for freight transport articulated trucks consume much less energy per tu-km than vans. But there are large variation in energy consumption per transport unit, depending on vehicle and fuel type; buses have *EI* values similar to those for trucks and gasoline cars have values of over 1.6 MJ/tu-km. Considering combined traffic and infrastructure use, the most inefficient modes using gasoline and diesel technologies are motorcycles and diesel vans, due to their low load factors. Considering only infrastructure use, motorcycles, vans and buses consume more energy per transport unit due to low AAHTs. Differences in *EI* between passenger and freight transport modes are similar for gasoline- and diesel-powered vehicles.

In terms of statistical significance, ANOVA test confirm significance of the mean *EI* and that the *EI* estimates for the twos slope differ and increase with slope. Similarly, the energy consumption estimates for the toll highway sections for the 10% and 30% level of HDVs show an increasing and highly significant trend. Significant differences between vehicle types, section energy consumption, and *EI* estimates are also observed. Sensitivity analysis of the input parameters defining energy consumption in Eq. (1) and *EI* in Eq. (3) show that increasing the input parameters by 20% results energy consumption increases significantly by 13.3%, 12.7% and 8.6%, while increasing the input parameters by 20%, *EI* increases by 9.3%, 7.0%, 6.3% and 5.8%.

4. Conclusions

The paper has examined the energy consumption and interurban toll highway transport in Spain. The energy intensities of the 202 sections studied carry 79.1% of traffic on the country's toll highways but relatively little traffic compared with free highways; *EI* values for cars are many times lower than those for motorcycles. The energy intensity of buses is significantly higher than that of cars because of the greater infrastructure resources required. Equally, while the *EI* values for articulated trucks are significantly lower than those for rigid trucks, the values for vans are many times higher likely because of capacity variations across the vehicle types. Regarding the various road sections most of the differences found in *EI* are due to the highways' slopes.

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